(12) UK Patent Application (19) GB (11) 2 338 781 (13) A

(43) Date of A Publication 29.12.1999

(21) Application No 9805358.0

(22) Date of Filing 14.03.1998

(71) Applicant(s)
British Aerospace Public Limited Company
(Incorporated in the United Kingdom)
PO Box 87, Warwick House,
Farnborough Aerospace Centre, FARNBOROUGH, Hants, GU14 6YU, United Kingdom

(72) Inventor(s)
Christopher Fell
Colin Henry John Fox

(74) Agent and/or Address for Service
British Aerospace Public Limited Company
Corp IP Department, PO Box 87, Lancaster House, Farnborough Aerospace Centre, FARNBOROUGH, Hampshire, GU14 6YU, United Kingdom

(51) INT CL^6
G01C 19/56

(52) UK CL (Edition Q)
G1G GPGA

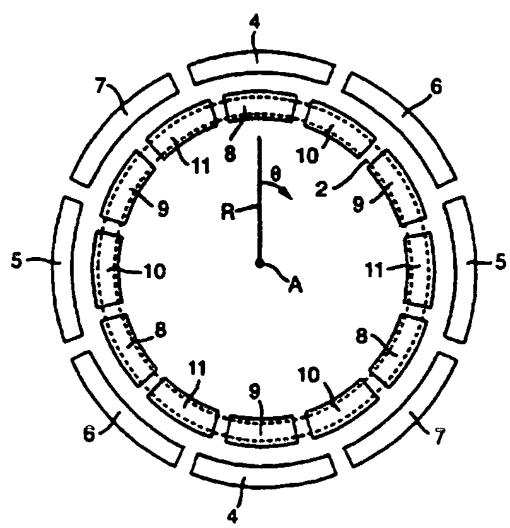
(56) Documents Cited
GB 2318184 A

(58) Field of Search
UK CL (Edition P) G1G GPGA
INT CL^6 G01C 19/56
ONLINE:WPI, IFIPAT, JAPIO, INSPEC

(54) Abstract Title
A Gyroscope

(57) A gyroscope for sensing rate on at least two axes includes a substantially planar vibratory resonator (2) having a ring or hoop like shape, carrier mode drive means (4) for causing the resonator (2) to vibrate in a $\cos n_1\theta$ in-plane carrier mode where n_1 has an integer value of 2 or more. The gyroscope also includes support means (3) for flexibly supporting the resonator (2), carrier mode pick off means (5) for sensing in-plane movement of the resonator, X axis response mode pick off means (8) for sensing out-of-plane $\cos n\theta$ response mode movement of the resonator in response to rotation of the gyroscope around the X axis, where n has a value of n_1+1 or n_1-1, and Y axis response mode pick off means (10) for sensing out-of-plane $\sin n\theta$ response mode movement of the resonator (2) in response to rotation of the gyroscope about the Y axis where n has a value n_1+1 or n_1-1, identical to that for the X axis response mode.

Fig.12.



GB 2 338 781 A

Fig.1a.

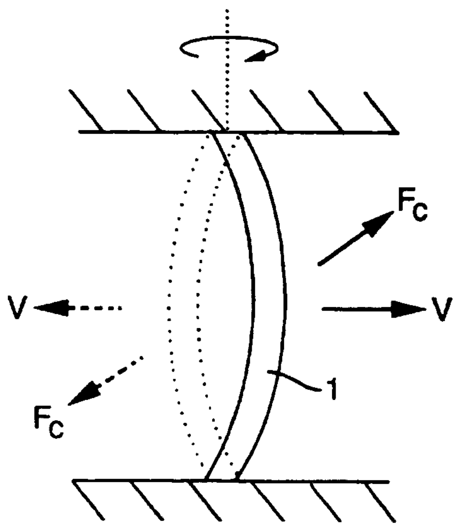


Fig.1b.

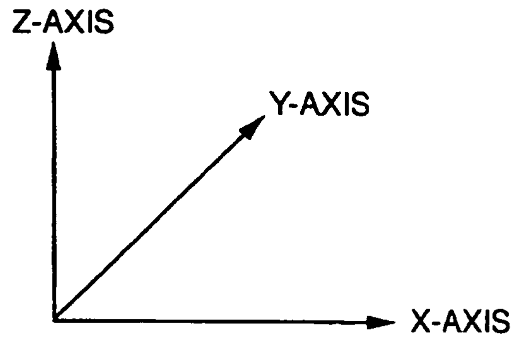


Fig.2a.

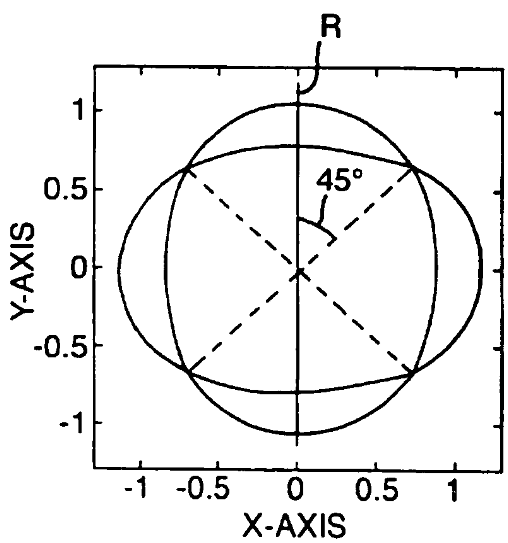


Fig.2b.

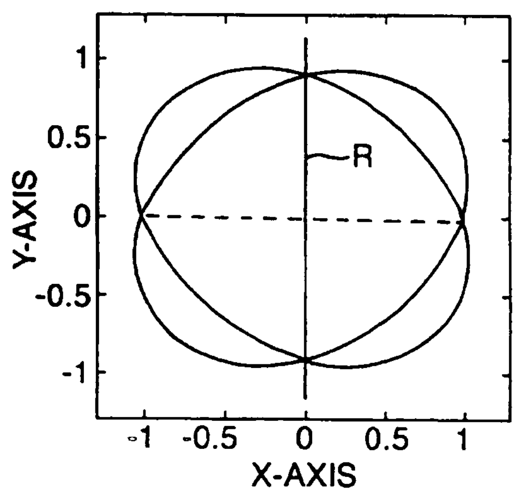


Fig.3a.

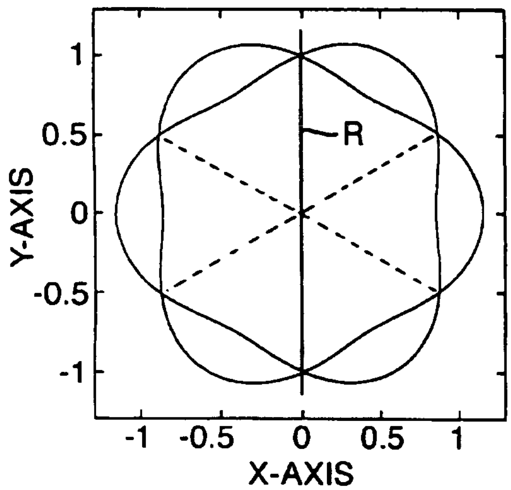


Fig.3b.

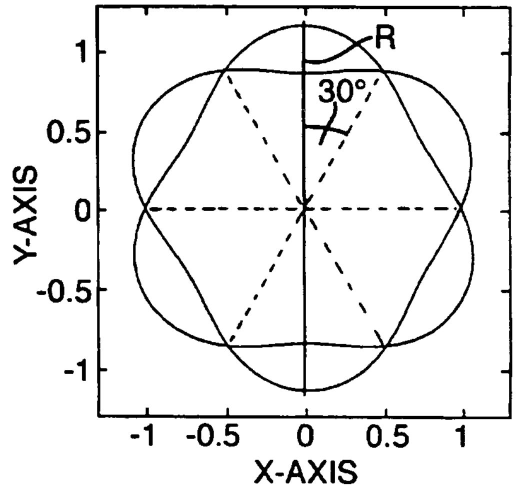


Fig.4a.

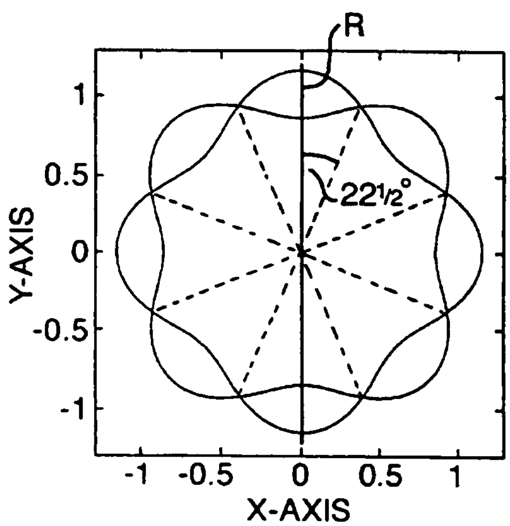


Fig.4b.

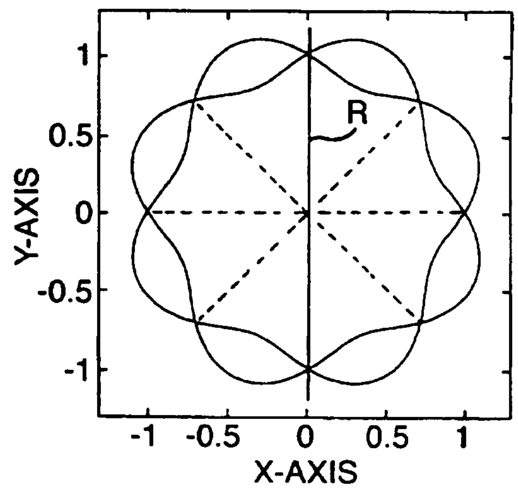


Fig.5a.

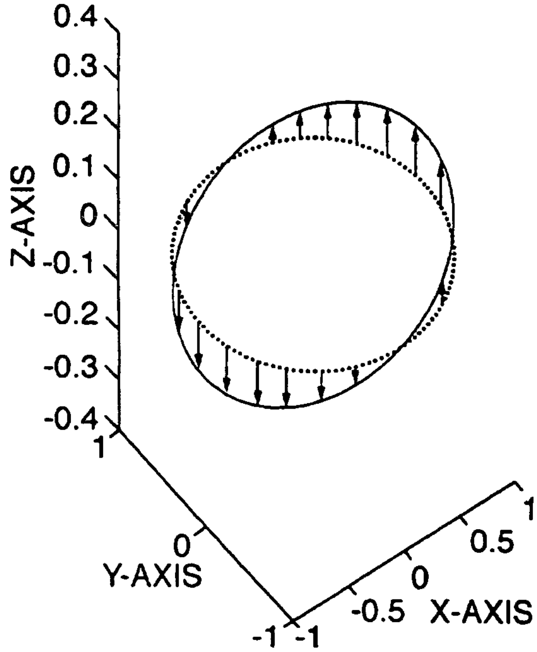


Fig.5b.

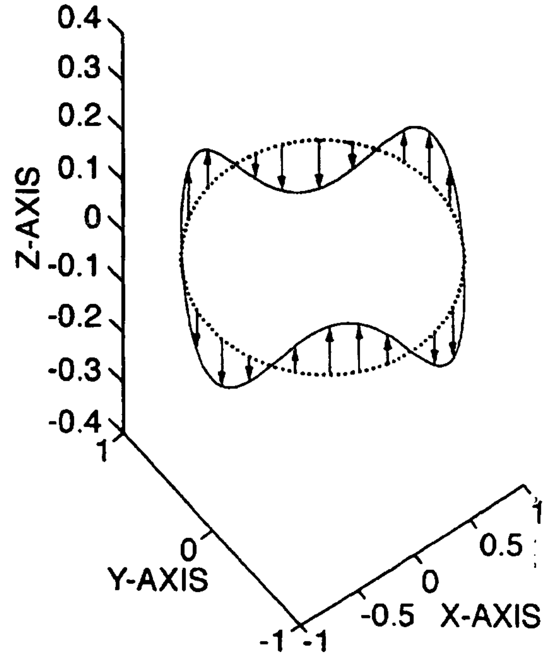


Fig.6a.

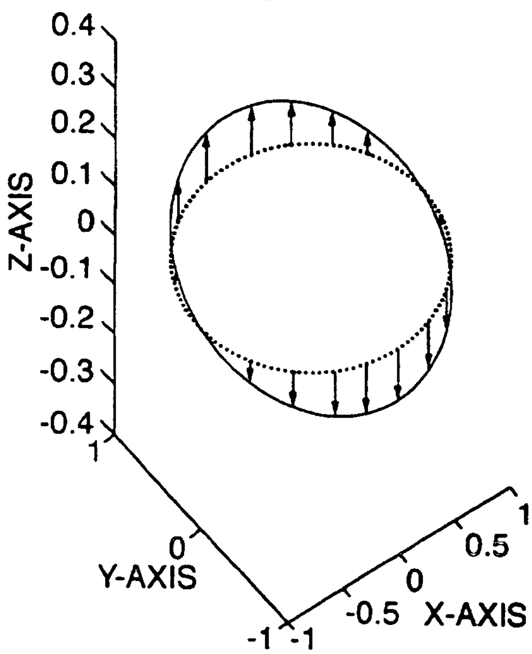


Fig.6b.

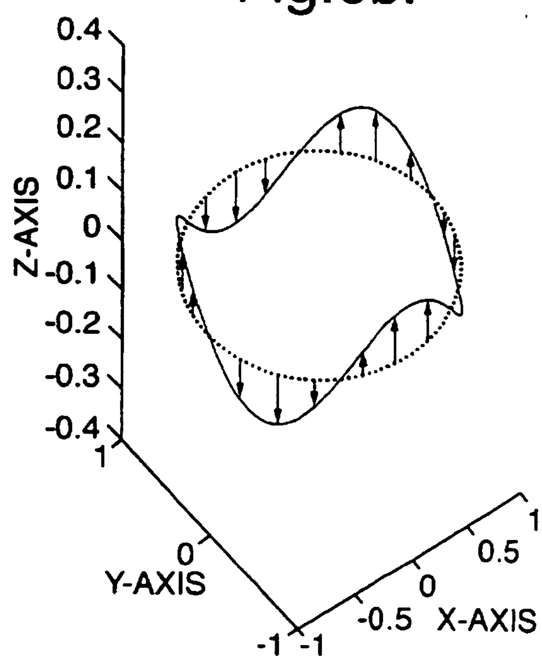


Fig.7a.

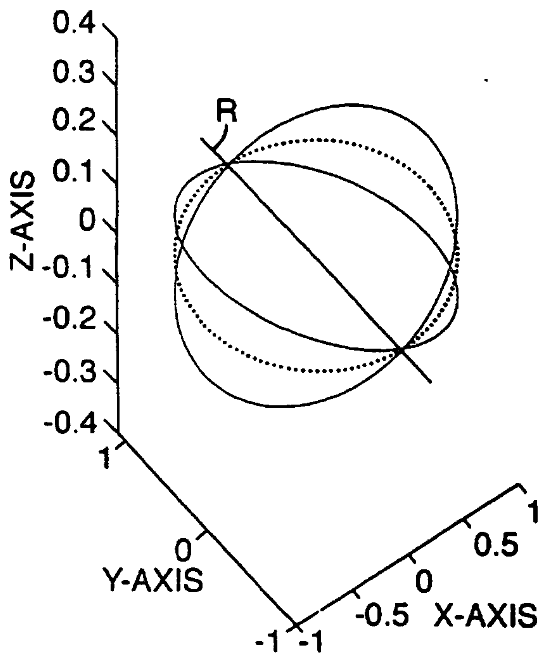


Fig.7b.

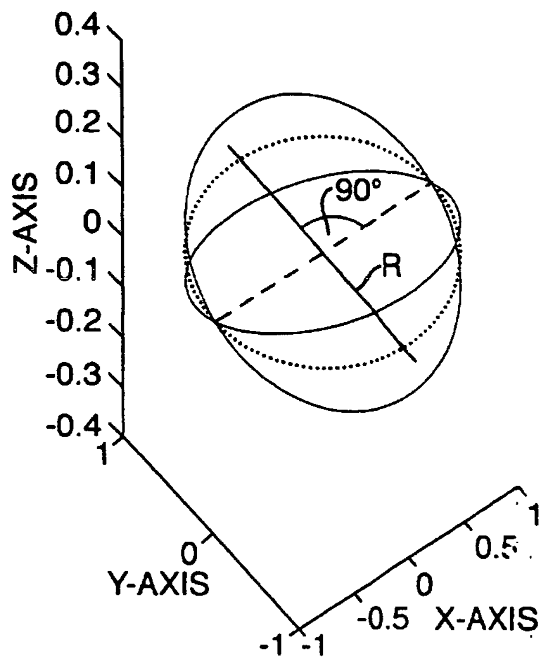


Fig.8a.

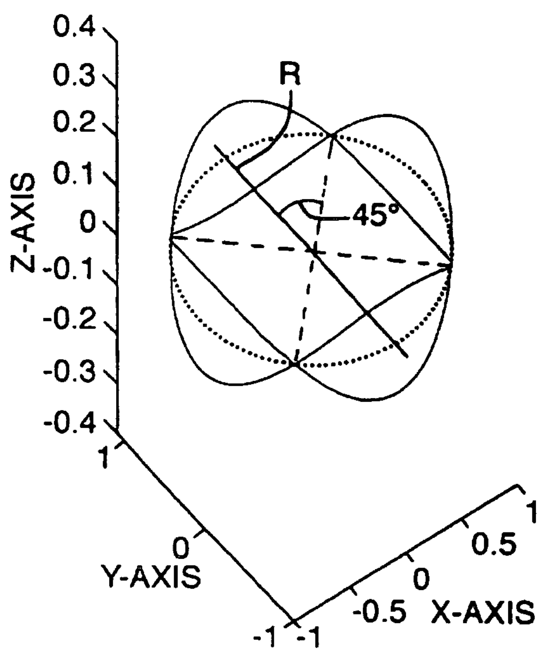


Fig.8b.

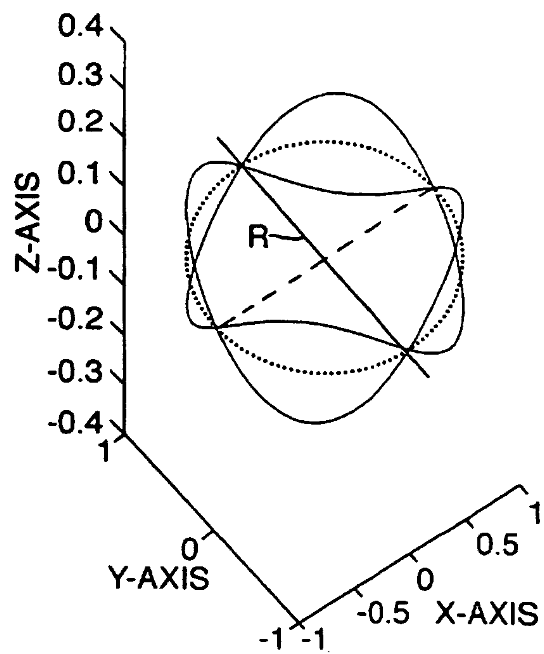


Fig.9a.

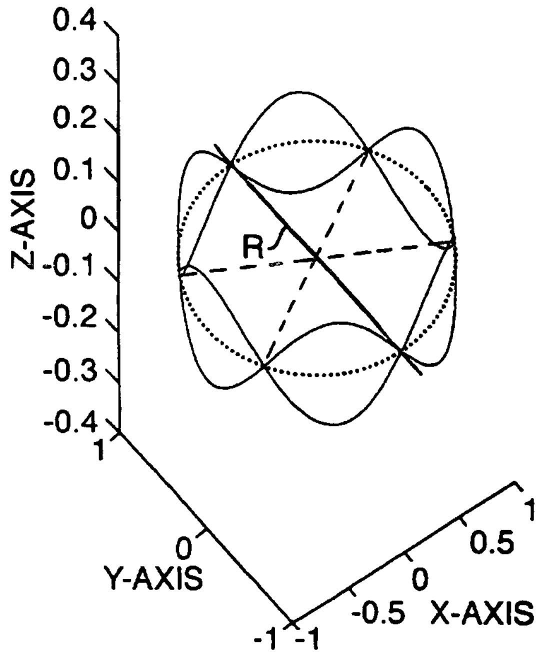


Fig.9b.

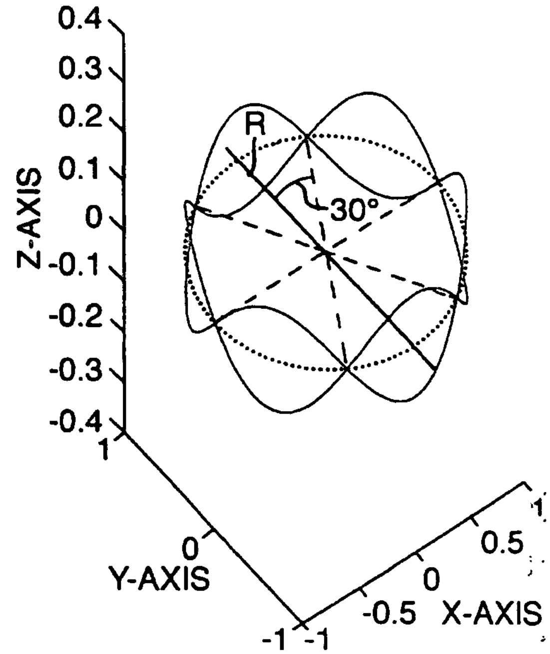


Fig.10a.

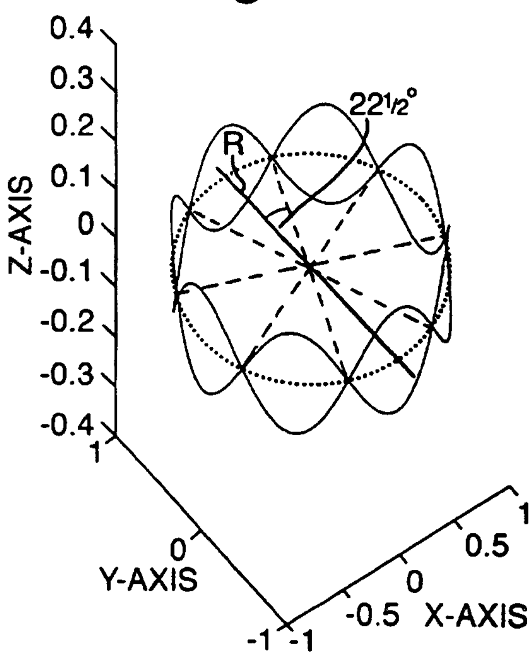


Fig.10b.

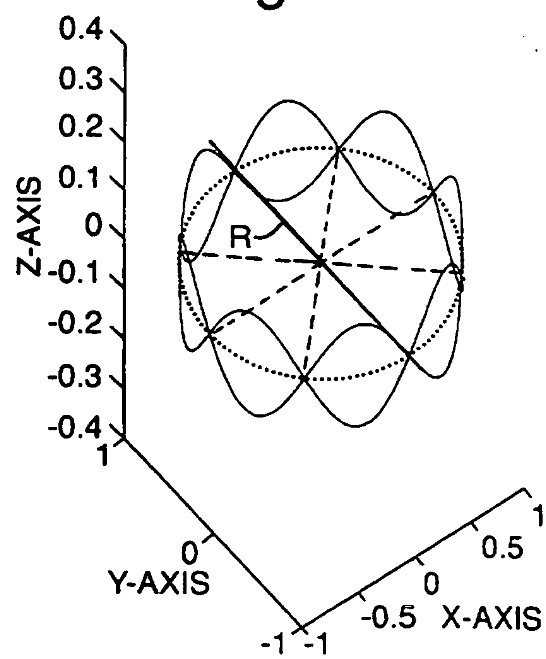


Fig.11a.

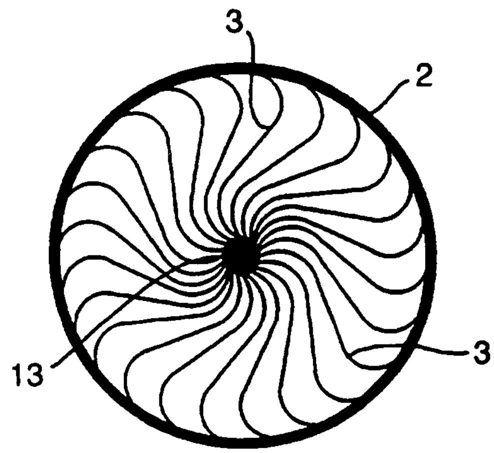


Fig.11b.

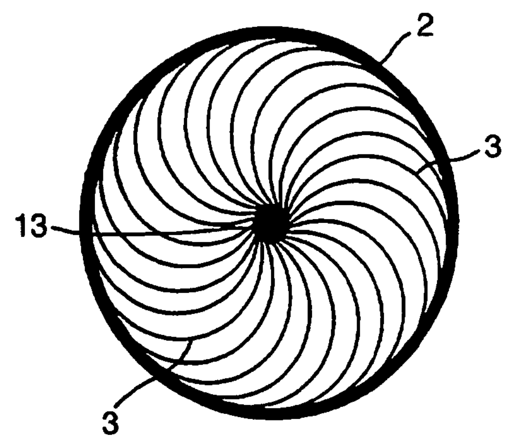


Fig.12.

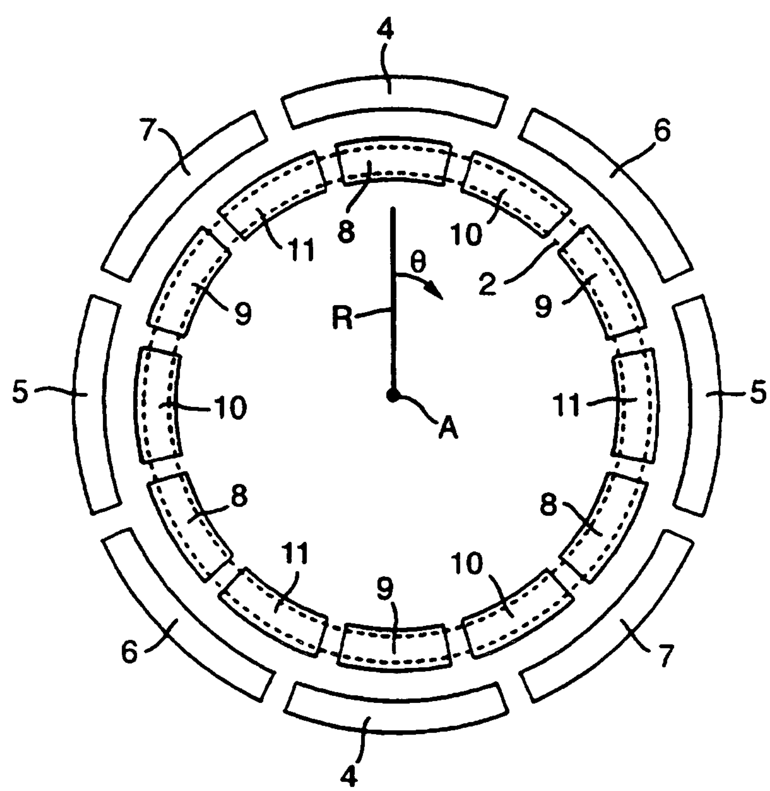


Fig.13.

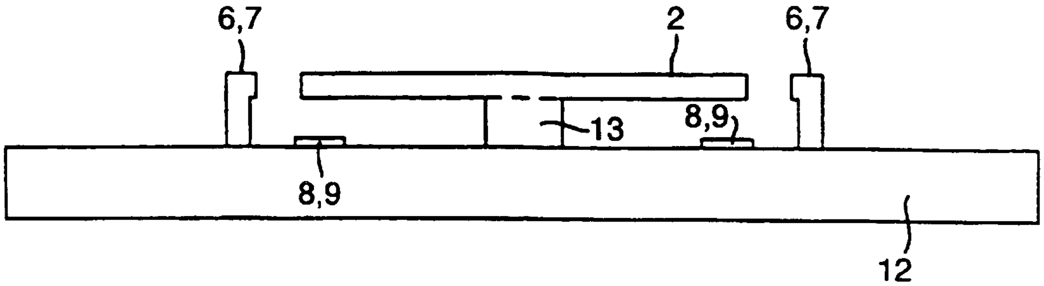


Fig.14.

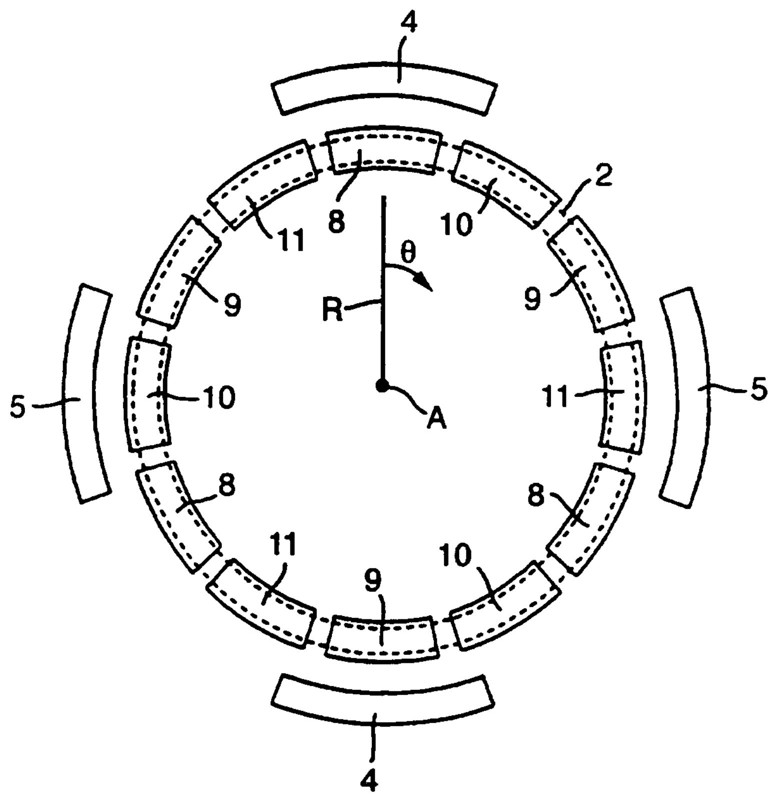


Fig.15.

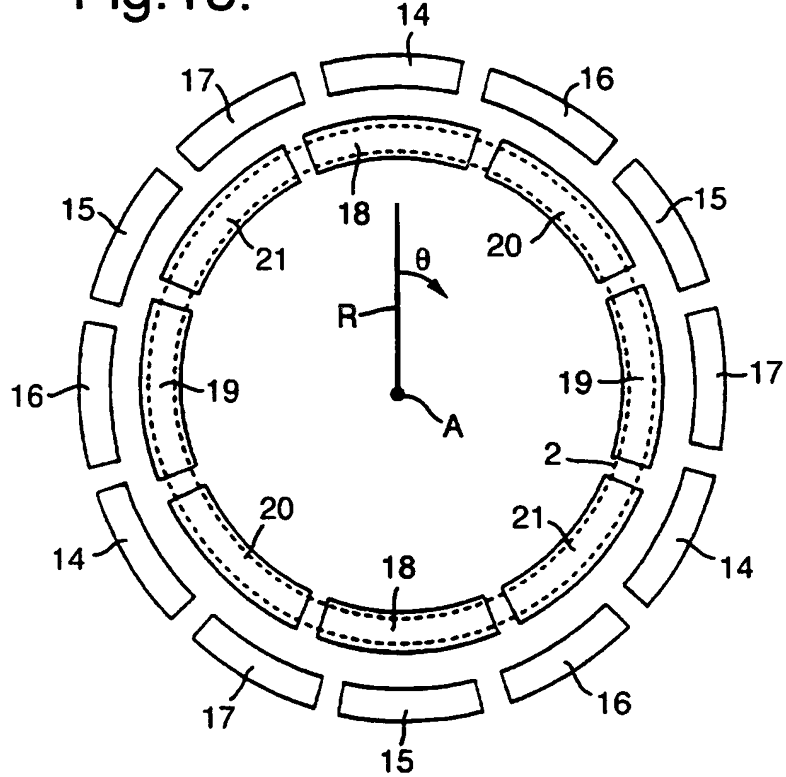

14
17
16
15
18
20
21
θ
R
16
19
19
17
A
2
20
21
14
18
14
17
16
15

Fig.16.

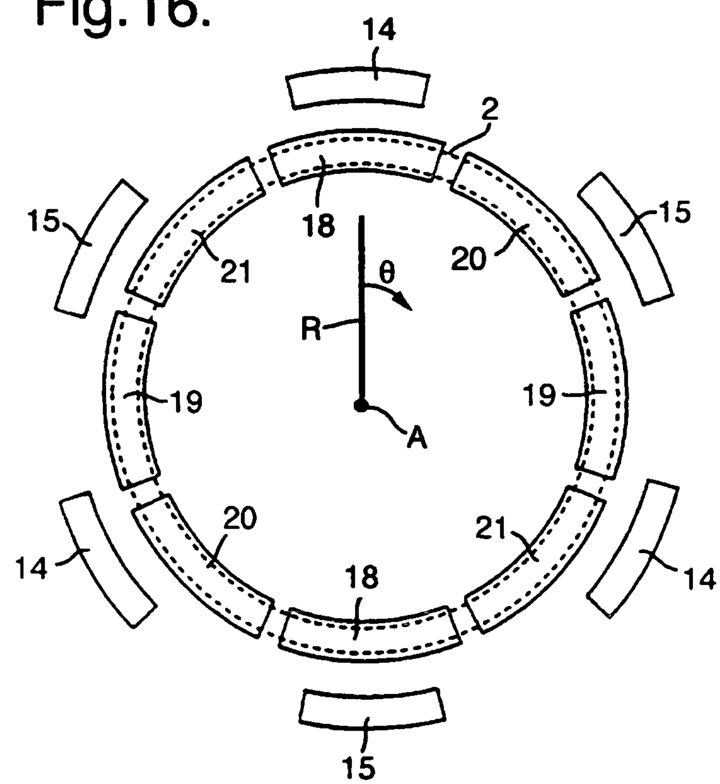

14
2
15
18
20
21
θ
R
19
19
A
20
21
14
18
14
15

Fig.17.

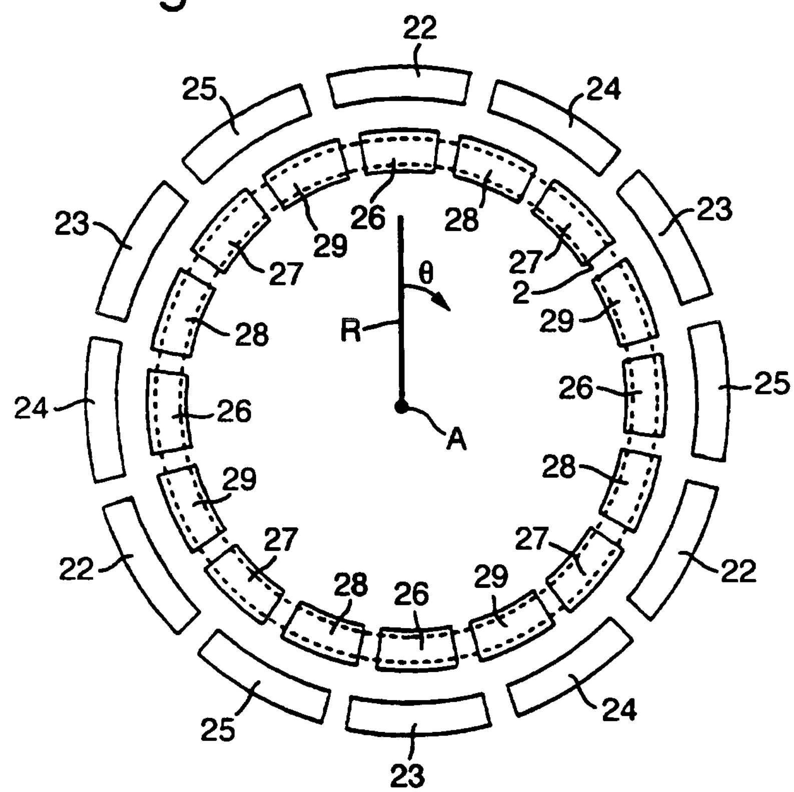
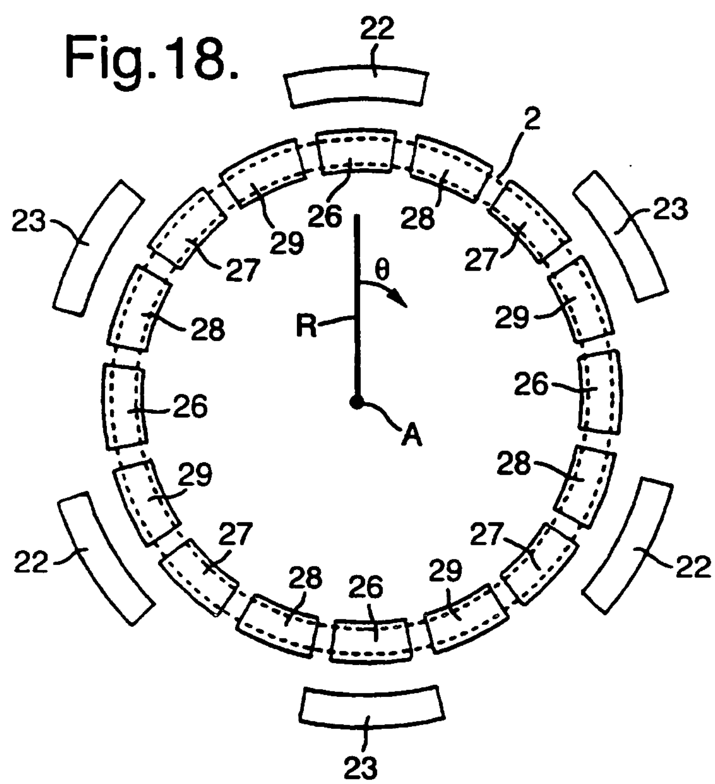


Fig.18.



2338781

A GYROSCOPE

This invention relates to a gyroscope suitable sensing rate on at least two axes, and preferably on three axes.

Vibrating structure gyroscopes may be fabricated using a variety of different structures as the resonant element. These include beams, tuning forks, cylinders, hemispherical shells and rings. Successful commercial exploitation is dependent upon optimising the device performance while minimising the cost. An additional goal for some applications is reducing the size of the device.

Some conventional vibrating structure gyro designs are suitable for fabrication using modern micro-machining techniques. These may be constructed from bulk Silicon, polysilicon or electro-formed metal. These fabrication methods provide the capability of producing miniature gyros in high volume and at reduced cost.

Many applications for gyroscopic devices require rate sensitivity about all three axes. Conventional vibrating structure gyros provide single axis rate sensitivity and therefore three devices are required which must be aligned along orthogonal axes. A vibrating structure gyro incorporating a resonator design which is inherently capable of sensing around three axes simultaneously would therefore

be of great benefit. A single device would thus replace three conventional single axis units with obvious cost benefits. Also, the process of mounting and aligning the three single axis gyros would not be required.

There is thus a need for an improved gyroscope which can sense rate on at least two axes.

According to a first aspect of the present invention there is provided a gyroscope for sensing rate on at least two axes, including a substantially planar vibratory resonator having a substantially ring or hoop-like shape structure with inner and outer peripheries extending around a common axis, carrier mode drive means for causing the resonator to vibrate in a $\cos n_1\theta$ in-plane carrier mode, where n_1 has an integer value of 2 or more, support means for flexibly supporting the resonator and for allowing the resonator to vibrate, in response to the carrier mode drive means, relative to the support means, carrier mode pick-off means for sensing in-plane movement of the resonator, X axis response mode pick-off means for sensing out-of-plane $\cos n\theta$ response mode movement of the resonator in respect to rotation of the gyroscope around the X axis, where n has a value of n_1+1 or n_1-1, and Y axis response mode pick off means for sensing out-of-plane $\sin n\theta$ response mode movement

of the resonator in respect to rotation of the gyroscope about the Y axis, where n has a value of n_1+1 or n_1-1, identical to that for the X axis response mode.

Preferably the gyroscope includes X axis response mode drive means for nulling the X axis response mode movement of the resonator to permit the gyroscope to be operated in a forced feedback configuration.

Conveniently the gyroscope includes Y axis response mode drive means for nulling the Y axis response mode movement of the resonator to permit the gyroscope to be operated in a forced feed back configuration.

Advantageously for sensing rate about two axes the support means includes a plurality of flexible legs flexibly connecting the resonator to a support, with the number of legs N_T being given by $N_T=4n$ and with the angular separation between the legs being given by $360°/N_T$.

Preferably for sensing rate about three axes the gyroscope includes Z axis response mode pick off means for sensing in-plane Sin $n_1\theta$ response mode movement of the resonator in respect to rotation of the gyroscope around the Z axis, where n_1 has an integer value of 2 or more, identical to that for the in-plane carrier mode.

Conveniently the gyroscope for sensing rate about three axes includes Z axis response mode drive means for nulling the Z axis response mode movement of the resonator to permit the gyroscope to be operated in a forced feedback configuration.

Advantageously the support means includes a plurality of flexible legs flexibly connecting the resonator to a support, with the number of legs N_T being given by $N_T=4nn_1$ and with the angular separation between the legs being given by $360°/N_T$.

Preferably in a gyroscope of the present invention for sensing rate about two axes the carrier mode is an in-plane Cos2θ mode, with the carrier mode drive means including two drive elements, for initiating the carrier mode motion, located at 0° and 180° with respect to a fixed reference axis in the plane of the resonator, with the carrier mode pick off means including two pick off elements, for detecting the carrier mode motion, located at 90° and 270° with respect to the fixed reference axis, wherein the X axis response mode is a Cos 3θ mode, with the X axis pick off means including three pick off elements located at 0°, 120°, and 240° with respect to the fixed reference axis, with the X axis drive means including three drive elements located at 60°, 180° and

300° with respect to the fixed reference axis, and wherein the Y axis response mode is a Sin 3θ mode, with the Y axis pick off means including three pick off elements located at 30°, 150° and 270° with respect to the fixed reference axis and with the Y axis drive means including three drive elements located at 90°, 210° and 330° with respect to the fixed reference axis, which X and Y axis drive and pick off elements are operable to detect and nullify the response mode motions.

Alternatively the carrier mode is an in-plane Cos 3θ mode, with the carrier mode drive means including three drive elements located at 0°, 120° and 240° with respect to a fixed reference axis in the plane of the resonator, with the carrier mode pick off means including three pick off elements located at 60°, 180° and 300° with respect to the fixed reference axis, wherein the X axis response mode is a Cos 2θ mode, with the X axis pick off means including two pick off elements located at 0° and 180° with respect to the fixed reference axis, with the X axis drive means including two drive elements located at 90° and 270° with respect to the fixed reference axis, and wherein the Y axis response mode is a Sin 2θ mode, with the Y axis pick off means including two pick off elements located at 45° and 225° with

respect to the fixed reference axis and with the Y axis drive means including two drive elements located at 135° and 315° with respect to the fixed reference axis.

Conveniently the carrier mode is an in-plane Cos 3θ mode, with the carrier mode drive means including three drive elements located at 0°, 120° and 240° with respect to a fixed reference axis in the plane of the resonator, with the carrier mode pick off means including three pick off elements located at 60°, 180° and 300° with respect to the fixed reference axis, wherein the X axis response mode is a Cos 4θ mode, with the X axis pick off means including four pick off elements located at 0°, 90°, 180° and 270° with respect to the fixed reference axis, with the X axis drive means including four drive elements located at 45°, 135°, 225° and 315° with respect to the fixed reference axis and wherein the Y axis response mode is a Sin 4θ mode, with the Y axis pick off means including four pick off elements located at 22.5°, 112.5° and 292.5° with respect to the fixed reference axis, and with the Y axis drive means including four drive elements located at 67.5°, 157.5°, 247.5° and 337.5° with respect to the fixed reference axis.

Advantageously a gyroscope for sensing rate of three axes, includes Z axis response mode pick off means for

sensing in-plane Sin 2θ response mode movement of the resonator, which Z axis pick off means includes two pick off elements located at 45° and 225° with respect to the fixed reference axis, and including Z axis response mode drive means having two drive elements located at 135° and 315° with respect to the fixed reference axis.

Preferably a gyroscope for sensing rate on three axes, includes Z axis response mode pick off means for sensing in-plane Sin 3θ response mode movement of the resonator, which Z axis pick off means includes three pick off elements located at 90°, 210° and 330° with respect to the fixed reference axis, and including Z axis response mode drive means having three drive elements located at 30°, 150° and 270° with respect to the fixed reference axis.

Advantageously the resonator is made from metal, quartz, polysilicon or bulk silicon.

Advantageously the drive means and the pick off means are electrostatic, electromagnetic, piezoelectric or optical.

For a better understanding of the present invention, and to show how the same may be carried into effect, reference will now be made, by way of example, to the accompanying drawings in which:_

Figure 1a is a schematic diagram of a vibrating structure gyroscope not according to the present invention,

Figure 1b shows the three orthogonal axes along which the velocity, rotation and force vectors lie with the structure of Figure 1a,

Figures 2a and 2b show graphically the shapes of mode pairs exhibiting $Cosn_1\theta$ and $Sinn_1\theta$ radial displacements for $n_1=2$,

Figures 3a and 3b are graphical shapes similar to those of Figures 2a and 2b for n=3,

Figures 4a and 4b are graphical shapes similar to those of Figures 2a and 2b and Figures 3a and 3b but for $n_1=4$,

Figures 5a and 5b are graphical representations on three axes for the force components generated by a rotation of a gyroscope according to the present invention about the Y axis, for a $Cos2\theta$ in-plane carrier mode.

Figures 6a and 6b are similar graphical representations to those of Figures 5a and 5b but representing rotation about the X axis,

Figures 7a and 7b are graphical representations on three axes of the vibration mode shapes exhibiting $Cosn\theta$ and $Sinn\theta$ out-of-plane displacements for n=1,

Figures 8a and 8b are graphical representations similar to those of Figures 7a and 7b but for n=2,

Figures 9a and 9b are graphical representations similar to those of Figures 8a and 8b but for n=3,

Figures 10a and 10b are graphical representations similar to those of Figures 9a and 9b but for n=4,

Figure 11a shows in plan view a diagrammatic example of a resonator and support legs suitable for use in a gyroscope according to the present invention,

Figure 11b shows in plan view a further resonator and support leg structure for use with a gyroscope according to the present invention,

Figure 12 is a schematic diagram in plan view of part of a gyroscope according to a first embodiment of the present invention showing drive and pick off elements,

Figure 13 is a cross sectional view on a diagonal of the structure of Figure 12 showing additional detail,

Figure 14 is a schematic plan view of part of a gyroscope according to a second embodiment of the present invention,

Figure 15 is a diagrammatic plan view of part of a gyroscope according to a third embodiment of the present invention,

Figure 16 is a diagrammatic plan view of part of a gyroscope according to a fourth embodiment of the present invention,

Figure 17 is a diagrammatic plan view of part of a gyroscope according to a fifth embodiment of the present invention and,

Figure 18 is a diagrammatic plan view of part of a gyroscope according to a sixth embodiment of the present invention.

A common feature of all conventional vibrating structure gyro designs is that they maintain a resonant carrier mode oscillation. This provides the linear momentum which produces the Coriolis force F_c, when the gyro is rotated around the appropriate axis. The magnitude of this force is given by:

$$F_c = 2\,\Omega\,m\,v \qquad \ldots \qquad (1)$$

where Ω is the applied rate, m is the mass and v the linear velocity. The velocity, rotation and force vectors lie along mutually orthogonal axes as shown in Figures 1a and 1b of the accompanying drawings.

One of the simplest implementations for a vibrating structure gyro is a beam 1 shown in Figure 1a. The carrier

mode vibration is a bending motion in the xz-plane as shown in Figures 1a and 1b. A rotation applied about the axis of the beam 1 (z-axis) will generate Coriolis forces which set the beam 1 into motion in the yz-plane, at the carrier frequency. The amplitude of motion in this axis will be proportional to the applied rotation rate. The sensitivity of such a device may be enhanced by designing the structure such that the Coriolis force directly excites a resonant mode. The amplitude of motion is then amplified by the Q of the response mode. For a simple beam made of isotropic material this will be achieved using a beam of square cross-section where the X and Y dimensions are matched.

A rotation about the Y-axis will also induce Coriolis forces in the beam 1. These will act along the length of the beam (z-axis). The beam is extremely stiff in this direction and is therefore insensitive to these forces. However this simple linear vibration along a single axis is able to respond to rotations around two axes. Implementation of a practical gyroscope based on these responses requires a resonator design that enables these Coriolis force components to couple directly into response modes along the appropriate axes.

In order to produce a gyroscope capable of sensing rate along three axes the carrier mode motion must contain velocity components along two orthogonal axes. The structure must also be designed such that the Coriolis forces induced as a result of rotation about each axis couple into response modes whose resonant frequency may be matched to that of the carrier. Planar ring structures utilising $\mathrm{Cos}n_1\theta$ in-plane carrier modes (where θ is the angular location around the ring circumference relative to a fixed datum and n_1 has a fixed integer value of 2 or more, are particularly suited to this application. The $n_1=1$ mode is not a suitable carrier as it is a rigid body translation of a ring resonator and thus only has velocity components along a single axis.

For perfect ring resonator structures the $\mathrm{Cos}n_1\theta$ in-plane vibration modes exist as degenerate pairs at a mutual angle of $(90/n_1)^\circ$. The $\theta=0^\circ$ reference axis R for the modal diagrams is along the Y-axis in the positive direction. Using this fixed reference the mode pairs will have shapes exhibiting $\mathrm{Cos}n_1\theta$ and $\mathrm{Sin}n_1\theta$ radial displacements. The mode shapes for $n_1=2$ are shown in Figures 2a and 2b. The two extremes of maximum displacement from the unexcited ring position, during a single vibration

cycle, are shown for each mode of the pair. The axes indicate the displacement from the unexcited ring position for a ring of radius 1.0 (arbitrary units). The modes exist at a mutual angle of 45°. The mode shapes for $n_1=3$ are similarly shown in Figures 3a and 3b. These exist at a mutual angle of 30°. The corresponding shapes for the $n_1=4$ modes are shown in Figures 4a and 4b and exist at a mutual angle of 22.5°.

Vibrating structure gyro designs using ring structures, capable of sensing rate about a single axis, are well known. These use one of the in-plane $\text{Cos}\,n_1\theta$ mode pair (typically $n_1=2$) as the carrier. A rotation about the axis normal to the plane of the ring (z-axis) couples energy into the second mode of the pair with the induced amplitude of motion being proportional to the applied rate.

Using these carrier modes, rotations about axes in the plane of the ring will also give rise to Coriolis forces. These will act along the z-axis and will tend to set the ring into out-of-plane motion. The distribution of these forces will vary with angular position θ and, for rotation about the Y-axis, Ω_Y, will be given by:

$$F_c(\theta) = F_{n_1+1}\,\Omega_y \text{Sin}(n_1+1)\theta + F_{n_1-1}\,\Omega_y\, \text{Sin}\,(n_1-1)\,\theta \quad \ldots(2)$$

The parameters Fn_1+1 and Fn_1-1 are constants which depend on the precise geometry of the ring and the support means, the material and the value of n_1. The out-of-plane Coriolis force thus has components which vary as $\mathrm{Sin}(n_1+1)\theta$ and $\mathrm{Sin}(n_1-1)\theta$. For the same carrier mode, a rotation about the X-axis will induce Coriolis forces given by:

$$F_c(\theta) = F_{n_1+1}\,\Omega_x \mathrm{Cos}(n_1+1)\theta + F_{n_1-1}\,\Omega_y \mathrm{Cos}(n_1-1)\theta \qquad \ldots (3)$$

The out-of-plane Coriolis force in this instance has components varying as $\mathrm{Cos}(n_1+1)\theta$ and $\mathrm{Cos}(n_1-1)\theta$. By way of example, for the case where the carrier is the $\mathrm{Cos}2\theta$ in-plane mode shown in Figure 2a, a rotation about the Y-axis will generate force components which vary as $\mathrm{Sin}\theta$ and $\sin 3\theta$. These are shown in Figures 5a and 5b, respectively. A rotation about the X-axis will generate components which vary as $\mathrm{Cos}\theta$ and $\cos 3\theta$. These are shown in Figures 6a and 6b.

The z-axis displacement of the out-of-plane modes will also exhibit a $\mathrm{Cos}n\theta$ angular dependence and, like the in-plane modes these exist as degenerate pairs at a mutual angle of $(90/n)°$. The mode shapes for $n=1$ exist at a mutual angle of $90°$ (i.e. $\mathrm{Sin}\theta$ and $\mathrm{Cos}\theta$ radial displacements) and

are shown in Figures 7a and 7b. As with the previous modal diagrams, the two extremes of motion are shown with the rest position of the ring indicated by the broken lines. The corresponding plots for the n=2, 3 and 4 modes are shown in Figures 8a, 8b, 9a, 9b, 10a and 10b.

The functional forms of the Coriolis force components shown in Figures 5a and 6a precisely match those of the n=1 out-of-plane mode shown in Figures 7a and 7b. Similarly, the forms of the Coriolis force components shown in Figures 5b and 6b precisely match those of the n=3 out-of-plane modes shown in Figures 9a and 9b. Clearly, these modes may be directly excited as a result of the rotation induced Coriolis forces.

Examination of equations 2 and 3 indicates that any $\mathrm{Cos}\,n_1\theta$ in-plane carrier mode can couple into $\mathrm{Cos}(n_1+1)\theta$, $\mathrm{Sin}(n_1+1)\theta$, $\mathrm{Cos}(n_1-1)$ and $\mathrm{Sin}(n_1-1)\theta$ out-of-plane modes when rotated around the appropriate axis. To be of practical use in any gyro configuration, the amplitude of motion generated must be as large as possible to maximise the gyro sensitivity. This is achieved by matching the mode frequencies of the carrier and a chosen pair out-of-plane response modes. The resultant motion is thus amplified by the Q of the response mode vibration. The in-plane mode

frequencies are not affected by changing the depth (ie z-axis dimension) of the ring. The out-of-plane mode frequencies are directly sensitive to this parameter and may therefore be independently adjusted. By judicious control of the dimensions of the ring resonator and support structure it is possible to match the $\mathrm{Cos}n_1\theta$ in-plane carrier frequency with either the $\mathrm{Cos}(n_1+1)\theta$ and $\mathrm{Sin}(n_1+1)\theta$ or the $\mathrm{Cos}(n_1-1)\theta$ and $\mathrm{Sin}(n_1-1)\theta$ out-of-plane modes. It is therefore possible to design multi-axis gyro schemes using a variety of carrier and response mode combinations.

The Cos2θ carrier mode can couple into the Sinθ, Cosθ, Sin3θ and Cos3θ out-of-plane response modes. These are shown in Figures 7a, 7b, 9a and 9b respectively. The use of the Cos2θ carrier in combination with the Sin3θ and Cos3θ response modes according to the present invention is capable of being implemented as a three axis rate sensor.

The resonator in a vibrating structure gyro preferably is substantially planar having a ring or hoop like shape resonator structure 2 with inner and outer peripheries extending around a common axis A normal to a fixed reference axis R in the plane of the resonator structure 2, which axis R extends in the direction of the Y axis. The ring structure is supported by support means including a

plurality of compliant support legs 3. When driven in a Cos2θ carrier mode both the ring and support legs are in motion. However, the ring 2 is very stiff in comparison to the support legs 3 and the carrier frequency is predominantly set by the ring dimensions. This effectively isolates the resonator from the mounting and reduces environmental sensitivity.

The Sinθ and Cosθ out-of-plane modes (Figures 7a and 7b) will involve significant deflection and stress in the support legs 3 with insignificant distortion of the ring 2. Due to the compliance of the legs this Cosθ mode naturally occurs at a significantly lower frequency than the Cos2θ carrier. The Sin3θ and Cos3θ response modes (Figures 9a and 9b) distort and stress the ring significantly. Its natural mode frequency will therefore be significantly higher than that of the Cosθ mode. The Cos 2θ carrier and the Sin3θ and Cos3θ response mode frequencies may thus be matched with considerably less adjustment of the leg to ring stiffness ratio. This helps to maintain the environmental capability of the gyroscope.

When using the out-of-plane Cosθ response modes, the legs 3 will always transmit a non-zero torque to the support structure as the ring 2 rocks about the input rotation axis.

In contrast, the out-of-plane Sin3θ and Cos3θ response mode will not transmit any net reaction force to the support structure if an appropriate number of legs are used. This will be true for all Cosnθ modes where n>1.

Practical gyroscopes of the present invention may be constructed using higher order in-plane carrier modes. The Cos3θ in-plane mode (Figure 3b) may be used as the carrier in conjunction with either the Cos2θ and Sin2θ or the Cos4θ and Sin4θ out-of-plane response modes. These response modes are shown in Figures 8a, 8b, 10a and 10b respectively. The Cos4θ carrier (Figure 4a) will couple into the Sin 3θ, Cos3θ, Sin5θ and Cos5θ response modes. Corresponding combinations of higher order are also feasible. In practice, however, the higher order mode combinations become increasingly onerous to implement. The mode shapes become progressively more complex and require a larger number of discrete drive and pick off elements to excite and sense the vibrations. Also, the support legs 3 act as point spring masses which perturb the mode frequencies. The number and location of these legs need to be matched to the mode symmetry to avoid induced splitting of the degenerate mode frequencies. The number of legs required increases rapidly

with the mode order thus rendering some designs impractical on a small size gyroscope.

A three axis gyroscope according to the present invention may be constructed by using a combination of Sin2θ and Cos2θ in-plane and the Sin3θ and Cos3θ out-of-plane modes. This gyroscope requires the frequencies of four modes to be matched (one carrier plus three response modes). However, for a perfectly symmetric ring 2 of uniform thickness, the Sin2θ and Cos2θ mode pair will have identical frequencies. Similarly, the Sin3θ and Cos3θ mode pair will also be matched. Therefore, due to the high degree of symmetry, the design of the resonator dimensions is, in practice, reduced to an exercise in matching only two frequencies (ie those of the two degenerate mode pairs). For the dimensions commonly used in ring resonators designed for single axis operation the Cos3θ out-of-plane and Cos2θ carrier mode frequencies naturally occur relatively closely matched in frequency. Adjusting the depth (z-axis dimension) of the ring does not alter the in-plane frequencies. It does, however, have a distinct affect of the out-of-plane frequencies. Matching the Sin2θ, Cos2θ, Sin3θ and Cos3θ mode frequencies may therefore be achieved by appropriate adjustment of a single ring dimension.

In terms of the mode dynamics, the support legs 3 appear as point spring masses acting at the point of attachment which differentially perturb the mode frequencies. In order to prevent frequency splitting and maintain the positional indeterminacy of the modes, the number and location of the legs must be matched to the mode symmetry. For any $\mathrm{Sin}n_1\theta$ and $\mathrm{Cos}n_1\theta$ mode pair this necessitates the use of $4n_1$ equi-angularly spaced legs (where n_1 is 2 or more). The $\mathrm{Sin}2\theta$ and $\mathrm{Cos}2\theta$ in-plane modes therefore require 8 equally spaced legs. The $\mathrm{Sin}3\theta$ and $\mathrm{Cos}3\theta$ out-of-plane modes require 12 legs to maintain their indeterminacy. To satisfy this requirement simultaneously for both mode pairs implies the use of 24 legs equally spaced at 15° intervals around the ring 2. This number is the lowest common multiple of the in-plane and out-of-plane leg numbers and may be derived for any three axis gyro mode combination from the following expression:

$$\text{Number of legs } N_T = n \times n_1 \times 4 \quad \ldots \quad (4)$$

The angular spacing of these legs is given by $[360/N_T]°$.

For planar ring resonator structures the support legs 3 are designed such that the modal behaviour is dominated by the ring characteristics. This requires the legs to be

radially and tangentially compliant, in comparison to the ring itself. Many design variations are possible which achieve these requirements. Figures 11a and 11b show two possibilities for the twenty-four support leg structure of one embodiment of the present invention. These designs are consistent with the use of larger numbers of support legs 3.

Vibrating structure gyroscopes of the invention may be constructed using standard fabrication and machining techniques. They are also suitable for fabrication using micro-machining techniques. The principle of operation and drive and pick off orientations will be identical regardless of the fabrication route. The resonator may be constructed from any material possessing suitable mechanical properties including metal, quartz, polysilicon or bulk silicon. The ring 2 may be driven into oscillation using a variety of drive means. These include electrostatic, electromagnetic, piezo or optical means. The amplitude of motion may similarly be detected using electrostatic, electromagnetic, piezo or optical pick off means.

The preferred three axis gyroscope embodiment uses electrostatic drive and pick off means. The orientation of drive and pick off elements for this embodiment is shown in Figure 12. The location of the ring 2 is indicated by the

dashed lines. The in-plane Cos2θ carrier mode is driven into oscillation using drive elements 4 whose effective centres are located at 0° and 180° around the outer periphery of the ring 2 with respect to the fixed reference axis R. For each element, the surface normal to the plane of the ring 2 facing the ring circumference forms one plate of the capacitor with the facing segment of the ring circumference forming the other plate. The ring 2 is maintained at a fixed potential with respect to the drive elements 4. An oscillating voltage applied to the drive element plates at the carrier mode frequency will generate an electrostatic force setting the ring 2 into oscillation. Pick off elements 5, for the carrier mode located at 90° and $270^\circ$with respect to the fixed reference axis R, similarly form capacitors with the facing ring segments and are used to detect the motion of the ring 2 as the capacitor gap varies. Pick off elements 6 located at 45° and 225° with respect to the axis R detect the amplitude of the in-plane Sin2θ response mode when the gyroscope is rotated around the z-axis. Z axis drive elements 7 located at 135° and 315° with respect to the axis R, may be used to null the mode movement to allow the gyroscope to operate in a forced feedback configuration. When_ operated in this mode the

nulling drive is proportional to the applied rate. This mode of operation provides performance advantages over the open loop mode.

The Cos3θ out-of-plane response mode providing the X-axis rate sensitivity will have anti-nodes at 0°, 60°, 120°, 180°, 240° and 300° locations, with respect to the axis R, around the ring circumference. The sin3θ Y-axis response mode will have anti-nodes at 30°, 90°, 150°, 210°, 270° and 330° with respect to the axis R. Drive and pick off elements may be located at any appropriate combinations adjacent to these points. Conveniently, twelve plate like elements are positioned directly under the rim to form capacitors between said plates and the parallel facing segments of the bottom surface of the ring. Conveniently, the plates should extend beyond the inner and outer edges of the ring rim. The in-plane motion of the carrier mode will not therefore change the effective plate area and will not be inadvertently detected by these plate like elements. Elements 8 located at 0°, 120° and 240° are used as X-axis pick off elements. The signals from these elements will be in phase and may be conveniently summed together to give enhanced sensitivity in detecting the mode movement. Plate like elements 9 located at 60°, 180° and 300° with respect to

the axis R are used as drive elements with the same drive voltage being applied to all these elements to null the motion to facilitate force feedback operation. Similarly, plate like elements 10 located at 30°, 150° and 270° with respect to the axis R are the Y-axis pick off elements with plate like elements 11 located at 90°, 210° and 330°, with respect to the axis R forming the drive elements for that mode.

Figure 13 shows a cross-section view through the centre of the resonator ring 2 along the Y-axis showing additional detail of the device architecture. The X and Y axis drive and pick off elements are conductive sites laid onto the surface of an electrically insulating substrate layer 12. These element sites are connected via tracks to bond pads (not shown) which can be electrically connected to the control circuitry. The ring 2 is attached, via the support legs 3, to a central support pedestal 13. This pedestal extends beneath the ring 2 and attaches rigidly to the substrate layer 12 such that the ring and support legs are freely suspended above the substrate layer. The in-plane mode drives and pick off elements are rigidly attached to the substrate 12 with tracking and bond pads provided as require to enable connection to the control circuitry.

Modifications to this structure are possible. The addition of a second insulating substrate layer rigidly fixed above the resonator ring 2, duplicating the out-of-plane drive and pick off element capacitor plate array, would enhance the sensitivity of the gyroscope along the X and Y axes. This would, however, complicate the fabrication process and would not alter the essential design features or functionality of the gyroscope.

A two axis gyroscope according to the present invention may be fabricated using the same Cos2θ in-plane carrier mode and Sin3θ and Cos3θ out-of-plane response modes. For this embodiment the resonator design is such that the in-plane Sin2θ and Cos2θ mode frequencies are deliberately separated. Advantageously, this frequency split will fix the carrier mode position at a known angular location which may be aligned to the carrier mode drive and pick off means. The carrier mode frequency must still be matched to that of the out-of-plane response modes. If twelve support legs 3 are used then the symmetry of the Cos 3θ modes is maintained. This will, however, generate a splitting of the in-plane Sin2θ and Cos2θ modes and thus fix the mode positions as required. Generally, for two axis gyroscope

operation the required number of support legs is given by the following expression:

Number of legs N_T = nx4 . . . (5)

The angular spacing is $[360/N_T]°$.

This implementation will provide rate sensitivity about the X and Y axes only. The in-plane response mode drive and pick off means are thus not required. Figure 14 shows a schematic of the gyroscope layout for this embodiment. This is essentially the same as the three axis embodiment of Figures 12 and 13, with the exception of the absence of the Z axis in-plane response mode drive elements 7 and pick off elements 6 and the different number of support legs, and hence like reference numerals have been used. No further description will therefore be given.

A two or three axis gyroscope may be fabricated using Sin3θ and Cos3θ in-plane modes in conjunction with sin2θ and Cos2θ out-of-plane response modes. For the three axis embodiment the degeneracy of both the in-plane sin3θ and Cos3θ and out-of-plane Sin2θ and Cos2θ mode pairs must be maintained. This dictates the use of twenty-four support legs 3 on the resonator ring 2. A schematic of the orientation of the drive and pickoff elements is shown in Figure 15. The topology of the gyroscope is largely

identical to the previously described embodiments with the exception of the drive and pick off element layout. The Cos3θ in-plane carrier drive means elements 14 are located at 0°, 120° and 240° with respect to the fixed reference axis R with the pick off means elements 15 located at 60°, 180° and 300° with respect to the axis R. The Z axis sin3θ in-plane response mode drive elements 16 are located at 30°, 150° and 270° with respect to the axis R with the pick off elements 17 at 90°, 210° and 330° with respect to the axis R. The out-of-plane Cos2θ X axis response mode pick off elements 18 are located at 0° and 180° with the nulling drive elements 19 at 90° and 270° with respect to the axis R. The Y axis out-of-plane Sin2θ pick off elements 20 are located at 45° and 225° with respect to the axis R with the nulling Y axis drive elements 21 at 135° and 315° with respect to the axis R.

The two axis embodiment of this Cos3θ in-plane carrier and out-of-plane Sin2θ and Cos2θ response mode combination requires the in-plane mode degeneracy to be lifted. This may be achieved by the use of eight support legs. Otherwise, this embodiment differs from the three axis one only in the omission of the in-plane response mode drive

elements 16 and pick off elements 17. The drive and pick off means layout is shown in Figure 16.

A two or three axis gyroscope of the invention may be fabricated using a Sin3θ and Cos3θ in-plane and a Sin4θ and Cos4θ out-of-plane mode combination. The three axis embodiment requires the use of forty-eight support legs 3 to maintain all the appropriate mode symmetries. This embodiment is shown schematically in Figure 17. The Cos3θ in-plane carrier mode drives 22 are located at 0°, 120° and 240° with respect to the fixed reference axis R with the pick off elements 23 at 60°, 180° and 300° with respect to the axis R. The in-plane Z axis Sin3θ response mode drive elements 24 are located at 30°, 150° and 270° with respect to the axis R with the z axis Cos3θ mode in-plane pick off elements 25 at 90°, 210° and 300° with respect to the axis R.

The X axis Cos4θ out-of-plane response mode pick off elements 26 are located at 0°, 90°, 180° and 270° with respect to the fixed reference axis R, with X axis Cos4θ out-of-plane response mode nulling drive elements 27 at 45°, 135°, 225° and 315° with respect to the axis R. The Y axis Sin4θ out-of-plane response mode pick off elements 28 are located at 22.5°, 112.5° 202.5° and 292.5° with respect to the axis R with Y axis Sin4θ out-of-plane response mode nulling

drive elements 29 at 67.5°, 157.5°, 247.5° and 337.5° with respect to the axis R.

The corresponding two axis gyroscope embodiment of the invention requires sixteen support legs 3. The layout for this embodiment, shown in Figure 18, is otherwise identical to the three axis one of Figure 17 with the exception of the omission of the z axis in-plane response mode drive elements 24 and pick off elements 25. Like parts have been given like numbers to those of Figure 17 and will not be further described.

Two and three axis rate sensors may be fabricated using higher order in-plane and out-of-plane mode combinations. These will require progressively higher numbers of support legs to maintain the necessary mode symmetries and a larger number of drive and pick off elements. As a result of this these embodiments, while feasible, become progressively more complicated to fabricate, particularly in a small size gyroscope.

Additonally in a gyroscope of the invention for sensing rate about two axes, the resonator 2 and support means are dimensioned so that the $\mathrm{Cos}n_1\theta$ in-plane carrier mode and $\mathrm{Sin}n\theta$ and $\mathrm{Cos}n\theta$ out-of-plane response mode frequencies are matched, and for sensing rate about three axes the

dimensions are such that the $\cos n_1\theta$ in-plane carrier mode, $\sin n_1\theta$ in-plane response mode and $\sin n\theta$ and $\cos n\theta$ out-of-plane response mode frequencies are matched.

CLAIMS

1. A gyroscope for sensing rate on at least two axes, including a substantially planar vibratory resonator having a substantially ring or hoop-like shape structure with inner and outer peripheries extending around a common axis, carrier mode drive means for causing the resonator to vibrate in a $\cos n_1\theta$ in-plane carrier mode, where n_1 has an integer value of 2 or more, support means for flexibly supporting the resonator and for allowing the resonator to vibrate, in response to the carrier mode drive means, relative to the support means, carrier mode pick-off means for sensing in-plane movement of the resonator, X axis response mode pick-off means for sensing out-of-plane $\cos n\theta$ response mode movement of the resonator in respect to rotation of the gyroscope around the X axis, where n has a value of n_1+1 or n_1-1, and Y axis response mode pick off means for sensing out-of-plane $\sin n\theta$ response mode movement of the resonator in respect to rotation of the gyroscope about the Y axis, where n has a value of n_1+1 or n_1-1, identical to that for the X axis response mode.

2. A gyroscope according to claim 1, including X axis response mode drive means for nulling the X axis response

mode movement of the resonator to permit the gyroscope to be operated in a forced feedback configuration.

3. A gyroscope according to claim 1 or claim 2, including Y axis response mode drive means for nulling the Y axis response mode movement of the resonator to permit the gyroscope to be operated in a forced feed back configuration.

4. A gyroscope according to any one of claims 1 to 3, wherein for sensing rate about two axes the support means includes a plurality of flexible legs flexibly connecting the resonator to a support, with the number of legs N_T being given by $N_T=4n$ and with the angular separation between the legs being given by $360°/N_T$.

5. A gyroscope according to any one of claims 1 to 3, for sensing rate about three axes, including Z axis response mode pick off means for sensing in-plane Sin $n_1\theta$ response mode movement of the resonator in respect to rotation of the gyroscope around the Z axis, where n_1 has an integer value of 2 or more, identical to that for the in-plane carrier mode.

6. A gyroscope according to claim 5, including Z axis response mode drive means for nulling the Z axis response

mode movement of the resonator to permit the gyroscope to be operated in a forced feedback configuration.

7. A gyroscope according to claim 5 or claim 6, wherein the support means includes a plurality of flexible legs flexibly connecting the resonator to a support, with the number of legs N_T being given by $N_T=4nn_1$ and with the angular separation between the legs being given by $360°/N_T$.

8. A gyroscope according to claim 2, claim 3 or claim 4 when appended to claim 2 or claim 3 for sensing rate about two axes, wherein the carrier mode is an in-plane Cos2θ mode, with the carrier mode drive means including two drive elements, for initiating the carrier mode motion, located at 0° and 180° with respect to a fixed reference axis in the plane of the resonator, with the carrier mode pick off means including two pick off elements, for detecting the carrier mode motion, located at 90° and 270° with respect to the fixed reference axis, wherein the X axis response mode is a Cos 3θ mode, with the X axis pick off means including three pick off elements located at 0°, 120°, and 240° with respect to the fixed reference axis, with the X axis drive means including three drive elements located at 60°, 180° and 300° with respect to the fixed reference axis, and wherein the Y axis response mode is a Sin 3θ mode, with the Y axis pick

off means including three pick off elements located at 30°, 150° and 270° with respect to the fixed reference axis and with the Y axis drive means including three drive elements located at 90°, 210° and 330° with respect to the fixed reerence axis, which X and Y axis drive and pick off elements are operable to detect and nullify the response mode motions.

9. A gyroscope according to claim 2, claims 3 or claim 4 when appended to claim 2 or claim 3, wherein the carrier mode is an in-plane Cos 3θ mode, with the carrier mode drive means including three drive elements located at 0°, 120° and 240° with respect to a fixed reference axis in the plane of the resonator, with the carrier mode pick off means including three pick off elements located at 60°, 180° and 300° with respect to the fixed reference axis, wherein the X axis response mode is a Cos 2θ mode, with the X axis pick off means including two pick off elements located at 0° and 180° with respect to the fixed reference axis, with the X axis drive means including two drive elements located at 90° and 270° with respect to the fixed reference axis, and wherein the Y axis response mode is a Sin 2θ mode, with the Y axis pick off means including two pick off elements located at 45° and 225° with respect to the fixed reference axis and

with the Y axis drive means including two drive elements located at 135° and 315° with respect to the fixed reference axis.

10. A gyroscope according to claim 2, claim 3 or claim 4 when appended to claim 2 or claim 3, wherein the carrier mode is an in-plane Cos 3θ mode, with the carrier mode drive means including three drive elements located at 0°, 120° and 240° with respect to a fixed reference axis in the plane of the resonator, with the carrier mode pick off means including three pick off elements located at 60°, 180° and 300° with respect to the fixed reference axis, wherein the X axis response mode is a Cos 4θ mode, with the X axis pick off means including four pick off elements located at 0°, 90°, 180° and 270° with respect to the fixed reference axis, with the X axis drive means including four drive elements located at 45°, 135°, 225° and 315° with respect to the fixed reference axis and wherein the Y axis response mode is a Sin 4θ mode, with the Y axis pick off means including four pick off elements located at 22.50, 112.5° and 292.5° with respect to the fixed reference axis and with the Y axis drive means including four drive elements located at 67.5°, 157.5°, 247.5° and 337.5° with respect to the fixed reference axis.

11. A gyroscope according to claim 8, for sensing rate of three axes, include Z axis response mode pick off means for sensing in-plane Sin 2θ response mode movement of the resonator, which Z axis pick off means includes two pick off elements located at 45° and 225° with respect to the fixed reference axis, and including Z axis response mode drive means having two drive elements located at 135° and 315° with respect to the fixed reference axis.

12. A gyroscope according to claim 9 or claim 10, for sensing rate on three axes, includes Z axis response mode pick off means for sensing in-plane Sin 3θ response mode movement of the resonator, which Z axis pick off means includes three pick off elements located at 90°, 210° and 330° with respect to the fixed reference axis, and including Z axis response mode drive means having three drive elements located at 30°, 150° and 270° with respect to the fixed reference axis.

13. A gyroscope according to any one of claims 1 to 13, wherein the resonator is made from metal quartz, polysilicon or bulk silicon.

14. A gyroscope according to any one of claims 1 to 13, wherein the drive means and the pick off means are electrostatic, electromagnetic, piezoelectric or optical.

15. A gyroscope for sensing rate on at least two axes, substantially as hereinbefore described and as illustrated in Figures 12 and 13, Figure 15, Figure 16, Figure 17 or Figure 18 as modified or not by any of Figures 2a to 11b of the accompanying drawings.

The Patent Office

Application No:	GB 9805358.0	**Examiner:**	Ruth Patterson
Claims searched:	1-14	**Date of search:**	22 June 1998

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.P): G1G (GPGA)

Int Cl (Ed.6): G01C 19/56

Other: ONLINE; WPI, IFIPAT, JAPIO, INSPEC.

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
A	GB 2318184 A	(BRITISH AEROSPACE PLC) See whole document.	1

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.